Telomerase reverse transcriptase promoter mutations in tumors originating from the adrenal gland and extra-adrenal paraganglia

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Abstract

Hotspot mutations in the promoter of the telomerase reverse transcriptase (TERT) gene have been recently reported in human cancers and proposed as a novel mechanism of telomerase activation. To explore TERT promoter mutations in tumors originating from the adrenal gland and extra-adrenal paraganglia, a set of 253 tumors (38 adrenocortical carcinomas (ACCs), 127 pheochromocytomas (PCCs), 18 extra-adrenal paragangliomas (ea PGLs), 37 head and neck PGLs (HN PGLs), and 33 peripheral neuroblastic tumors) was selected along with 16 human neuroblastoma (NBL) and two ACC cell lines to assess TERT promoter mutations by the Sanger sequencing method. All mutations detected were confirmed by a SNaPshot assay. Additionally, 36 gastrointestinal stromal tumors (GISTs) were added to explore an association between TERT promoter mutations and SDH deficiency. TERT promoter mutations were found in seven out of 289 tumors and in three out of 18 human cell lines; four C228T mutations in 38 ACCs (10.5%), two C228T mutations in 18 ea PGLs (11.1%), one C250T mutation in 36 GISTs (2.8%), and three C228T mutations in 16 human NBL cell lines (18.75%). No mutation was detected in PCCs, HN PGLs, neuroblastic tumors as well as ACC cell lines. TERT promoter mutations preferentially occurred in a SDH-deficient setting (P=0.01) being present in three out of 47 (6.4%) SDH-deficient tumors vs zero out of 171 (0%) SDH-intact tumors.

Key Words
- TERT promoter mutations
- telomerase reverse transcriptase
- adrenocortical carcinomas
- paragangliomas
- neuroblastomas
- SDH deficiency
tumors. We conclude that TERT promoter mutations occur in ACCs and ea PGLs. In addition, preliminary evidence indicates a potential association with the acquisition of TERT promoter mutations in SDH-deficient tumors.

Introduction

Telomerase is a ribonucleoprotein complex consisting of the telomerase reverse transcriptase (TERT) catalytic subunit and the telomerase RNA component. Telomerase is responsible for the addition of telomeric repeats at the end of linear eukaryotic chromosomes, thereby maintaining the telomere length (Mocellin et al. 2013). Telomeres have two major functions in normal cells (Blasco & Hahn 2003, Mocellin et al. 2013). First, they function to protect chromosome ends from being recognized as DNA double-strand breaks by the DNA repair machinery that can result in fusion of chromosome ends and gross chromosomal alterations. Secondly, telomeres prevent 3’-DNA shortening during cell division that can trigger cellular senescence.

In cancer cells, which display uncontrolled proliferation, maintenance of telomeres is crucial to prevent senescence induction. As a consequence, tumor cells frequently show activation of mechanisms that protect telomeres and confer cellular immortalization. In over 90% of cases, tumor cells display constitutive telomerase activation (Blasco & Hahn 2003). While there exists evidence that telomerase activity is regulated at various levels including epigenetic mechanisms (Daniel et al. 2012, Castelo-Branco et al. 2013), posttranslational modification (Li et al. 1998, Kang et al. 1999), or nuclear translocation (Liu et al. 2001) of TERT, upregulation of TERT at the transcriptional level, via the inappropriate binding of transcription factors such as c-myc to the core promoter region (Greenberg et al. 1999, Wu et al. 1999, Daniel et al. 2012), appears to be the primary mechanism yielding telomerase activation.


The prevalence of TERT promoter mutations in follicular cell-derived thyroid cancer indicated that these mutations may be important in endocrine tumorigenesis (Landa et al. 2013, Liu et al. 2013a,c, Vinagre et al. 2013). Consistent with this prevalence, four independent research groups illustrated that more aggressive thyroid cancer subtypes were enriched for these mutations (Landa et al. 2013, Liu et al. 2013a,c, Vinagre et al. 2013). With regard to adrenocortical carcinomas (ACCs), a frequency of 12% has been recently shown in a single cohort (Liu et al. 2014). By contrast, no mutations have been observed in parafollicular cell-originated medullary thyroid carcinoma (Killela et al. 2013, Liu et al. 2013a,b,c, Vinagre et al. 2013), while these seem to be extremely rare genetic events in pheochromocytomas (PCCs) and paragangliomas (PGLs) (Vinagre et al. 2013, Liu et al. 2014). In the current study, we examined the presence of these mutations in tumor types originating from the adrenal gland and extra-adrenal paraganglia including ACCs, PCCs, extra-adrenal (ea) and head and neck- (HN-) PGLs, as well as peripheral neuroblastic tumors. Given that TERT promoter mutations occur preferentially in specific genetic backgrounds in various tumors, any association with SDH-deficient status in PCCs, PGLs, and gastrointestinal stromal tumors (GISTs) was explored.
Subjects and methods

Tumor tissue samples and cell lines

A total of 253 formalin-fixed and paraffin-embedded (FFPE) tumors were selected, including 38 ACC samples (Erasmus MC, Rotterdam, The Netherlands: 35 primary tumors, two recurrences, and one metastasis), 127 PCCs/18 ea PGLs/37 HN PGLs (Erasmus MC, Rotterdam, The Netherlands: 167 cases; UMC St Radboud, Nijmegen, The Netherlands: 12 cases; and Birmingham, UK: three cases), and 33 peripheral neuroblastic tumors (Erasmus MC, Rotterdam, The Netherlands: 167 cases; UMC St Radboud, Nijmegen, The Netherlands: 15 NBLs, eight ganglioneuroblastomas, and ten ganglioneuromas). Tumors with mutations in the SDH-x genes, such as SDHA, SDHB, SDHC, SDHD, and SDHAF2, display loss of immunohistochemical staining for SDHB (van Nederveen et al. 2009, Korpershoek et al. 2011). Given that loss of SDHB expression reflects SDH deficiency (Barletta & Hornick 2012), we will collectively use the term ‘SDH deficient’ for tumors displaying SDHB immunonegativity. As SDH deficiency also defines a subset of GISTs similar to the SDH-related PCC/PGL subgroup, an additional series of 36 GISTs was examined to explore the relationship between TERT promoter mutations and SDH deficiency in a non-endocrine tumor type.

All tumor samples were assessed anonymously according to the Proper Secondary Use of Human Tissue code established by the Dutch Federation of Medical Scientific Societies (http://www.federa.org). The Medical Ethical Committee of the Erasmus MC approved the study.

DNA isolation and TERT promoter mutation analysis

DNA isolation from tumors was carried out using standard procedures following manual microdissection of all tumor samples to ensure a >80% neoplastic cell content. Standard PCR was performed to amplify a 163 bp fragment of the TERT promoter region, covering all previously described mutations (C228T, CC229TT, CC242TT, and C250T, corresponding to nucleotide positions −124, −125, −138, and −145 from the translational start site (UCSC: chr5 nt 1 295 104)), using forward primer 5’-GTCTTGCCCCTTCACCTT-3’ and reverse primer 5’-CACGCCTGCCCTGAACACTC-3’. Subsequently, PCR products were used as templates for direct sequencing using the BigDye Terminator V3.1 cycle sequencing kit (Applied Biosystems). Products were analyzed on the ABI Prism 3130 Genetic Analyzer (Applied Biosystems).

TERT promoter mutations were confirmed by a SNaPshot assay using the ABI Prism SNaPshot Multiplex Kit (Applied Biosystems) as described previously (Allory et al. 2014). In brief, after the multiplex SNaPshot reaction, the products were treated with shrimp alkaline phosphatase to remove excess deoxyribonucleotide triphosphates, and subsequently were labeled and separated in a 25-min run on 36-cm-long capillaries in an automatic sequencer (ABI Prism 3130 Genetic Analyzer, Applied Biosystems). GeneScan Analysis Software, version 3.7 (Applied Biosystems) was used for data analysis. All experimental conditions are available on request. Probe sequences of the SNaPshot reaction are given in Supplementary Table 1, see section on supplementary data given at the end of this article.

SDHB/SDHA immunohistochemistry, mutation screening, and loss of heterozygosity analysis

SDH (immunohistochemistry (IHC) and/or mutation) status was known for 218 PCCs, ea PGLs, HN PGLs, and GISTs. To investigate the SDH status of the ACC samples included in the current study, these samples were arranged in a tissue microarray (TMA) format along with additional adrenocortical adenomas (ACAs), normal adrenal tissue, and control tissue samples (38 ACC, 17 ACA, five normal adrenal tissue, and 12 control tissue samples) using an automated TMA constructor (ATA-27 Beecher Instruments, Sun Prairie, WI, USA) available at the Department of Pathology, Erasmus MC. For each tumoral case, representative areas were selected and marked on a hematoxylin and eosin-stained slide. Accordingly, two tissue cores with a diameter of 1 mm were extracted from ‘donor’ block and brought into the ‘recipient’ paraffin block at predefined coordinates. SDHA and SDHB immunostaining procedures were performed on 4–5 μm TMA sections with a mouse monoclonal Ab14715 antibody.
(Mitosciences, Abcam, Cambridge, UK; 1:500 dilution) against SDHA and a rabbit polyclonal HPA002868 antibody (Sigma–Aldrich Corp., St. Louis, MO, USA; 1:400 dilution) against SDHB on an automatic Ventana Benchmark Ultra System (Ventana Medical Systems, Inc., Tuscon, AZ, USA). If the internal control (granular staining in endothelial cells) was positive, slides were considered as informative. From SDHB-immunonegative/SDHA-immunopositive ACCs, i) the entire SDHA, SDHB, SDHC, SDHD, and SDHAF2 coding sequences were assessed at the germline and somatic levels for mutations using an Ion AmpliSeq Custom Panel that was sequenced on the Ion Torrent Personal Genome Machine (PGM; Life Technologies) on 10 ng FFPE tumor DNA according to the manufacturer’s protocols. In short, libraries were made using the Ion AmpliSDefault 2.0 Library Kit. Template was prepared using the Ion OneTouch Template Kit and sequencing was performed with the Ion PGM Sequencing 200 Kit v2.0 on an Ion 316v2 chip. Data were analyzed using the Torrent Suite Software, version 3.6.2 (Life Technologies). Annotation of variant calls was performed with Annovar (http://www.openbioinformatics.org/annovar/; Wang et al. 2010) and facilitated using an in-house galaxy platform/server on which Annovar wrapper was installed (Giardine et al. 2005, Blankenberg et al. 2010, Goecks et al. 2010, Hyltemann et al. 2014). The variants with a read frequency higher than 10%, not known as common polymorphisms according to 1000G2012 April and ESP6500, non-synonymous with a minimum of five forward/reverse variant reads and 100 total depth reads were retained as interesting ones (mutations) (sequences of all primers and probes are available upon request); and large intragenic deletions using multiplex ligation-dependent probe amplification (MLPA) assay were analyzed using a commercially available kit (SALSA MLPA P226-B2; MRC Holland, Amsterdam, The Netherlands) and ii) loss of heterozygosity (LOH) analysis was performed for polymorphic microsatellite markers flanking the SDHB, SDHC, SDHD, and SDHAF2 genes as described previously (Papathomas et al. 2013).

RNA extraction and TERT expression analysis by quantitative real-time PCR

Total mRNA was extracted from human primary adrenal tissue (one ACC harboring a TERT promoter mutation, two ACCs without TERT promoter mutation, one ACA, and two normal adrenocortical tissue samples) or cell pellets (HEK and SW13 cell lines) using TRIzol reagent (Invitrogen Life Technologies) and the RNA-containing supernatant was purified using RNaseasy spin columns (Qiagen Benelux B.V.). First-strand cDNA synthesis was performed on 200 ng total RNA using qScript cDNA Supermix (Quanta Biosciences, Gaithersburg, MD, USA), followed by TERT-specific and hypoxanthine phosphoribosyltransferase 1 (HPRT1)-pre-amplification using PerfeCTa PreAmp SuperMix (Quanta Biosciences). The PreAmp product was diluted and used to assess human telomerase expression in all samples by quantitative real-time PCR in triplicate using TaqMan (Applied Biosystems) gene expression assays. TERT (TERT Hs00972656_m1) was measured relative to HPRT (HPRT1) expression. The relative amount of RNA was calculated by the 2－ΔΔCT method. Fold changes in gene expression were determined by comparing expression levels of tumor tissue or cell lines with normal adrenocortical tissue. No RNA was available to test the remaining tumors endowed with the C228T and C250T mutations.

Statistical analysis

Statistical analysis was performed using SPSS (IBM SPPS Statistics, version 20) on a series of 218 tumors (PCCs/PGLs/GISTs) of known SDH status. Fisher’s exact test was used to determine the relationships between the presence of a TERT promoter mutation and SDH deficiency. Statistical differences were considered to be significant when the P value is <0.05.

Results

Prevalence of TERT promoter mutations in various human tumors and cell lines

TERT promoter mutations were found in seven out of 289 tumors investigated with C228T being the most frequent substitution. There were four C228T mutations in 38 ACCs (10.5%), two C228T mutations in 18 ea PGLs (11.1%), and one C250T mutation in 36 GISTs (2.8%). Clinicopathological and genetic data of these patients are given in Table 1 in detail, while representative somatic TERT promoter mutations (C228T and C250T) detected both by the Sanger sequencing method and a SNaPshot assay are displayed in Fig. 1. Out of seven, six TERT promoter-mutated tumors were metastatic (Table 1). Although three out of four mutation-positive ACCs were characterized by highly aggressive biological behavior, we could not perform proper survival analysis due to the limited number of these cases. Mutations were not detected in any of the 127 PCCs, 37 HN PGLs, and 33 peripheral neuroblastic tumors.
The TERT promoter mutation C228T was found in three out of 16 (18.8%) human NBL cell lines (SJNB-10, SJNB-12, and SK-N-BE), while no mutations were present in the two ACC cell lines (Supplementary Table 2, see section on supplementary data given at the end of this article).

Enrichment of TERT promoter mutations in SDH-deficient tumors

Given that a subset of PCCs, PGLs, and GISTs is associated with germline SDH-x mutations and/or loss of SDHB immunoeexpression (collectively known as SDH-deficient tumors) and three out of 47 (6.4%) SDH-deficient tumors harbored a TERT promoter mutation, we analyzed the relationship between the SDH-deficient status and the presence of TERT promoter mutations. It has been demonstrated that TERT promoter mutations occur preferentially in SDH-deficient tumors (6.4 vs 0%; P=0.01).

Loss of SDHB expression in TERT promoter-mutated ACCs

Out of 55 adrenocortical tumor samples, one ACC harboring a TERT C228T mutation was SDHB immunonegative/SDHA immunopositive. SDHB/SDHA IHC was re-performed on whole-tissue sections in all four TERT promoter-mutated ACCs and accordingly confirmed the aforementioned finding. Mutational analysis did not reveal any pathogenic germline or somatic SDHB/C/D/AF2 mutations, while large intragenic SDHB, SDHD, and SDHAF2 deletions were detected only at the somatic level.

Table 1  Clinicopathological and genetic data of patients with TERT promoter-mutated tumors

<table>
<thead>
<tr>
<th>Case no.</th>
<th>Tumor type</th>
<th>Anatomic site</th>
<th>Sex</th>
<th>Age</th>
<th>TERT promoter mutation</th>
<th>SDH-deficient</th>
<th>Weiss score</th>
<th>Metastatic disease/site</th>
<th>Follow-up status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ACC</td>
<td>Adrenal gland</td>
<td>F</td>
<td>50</td>
<td>C228T</td>
<td>No</td>
<td>5</td>
<td>Yes/liver</td>
<td>9 mo/DOD</td>
</tr>
<tr>
<td>2</td>
<td>ACC</td>
<td>Adrenal gland</td>
<td>M</td>
<td>51</td>
<td>C228T</td>
<td>No</td>
<td>6</td>
<td>Yes/liver, lung, and bone</td>
<td>12 mo/DOD</td>
</tr>
<tr>
<td>3</td>
<td>ACC</td>
<td>Adrenal gland</td>
<td>M</td>
<td>42</td>
<td>C228T</td>
<td>Yes</td>
<td>8</td>
<td>Yes/liver, lung, and LNs</td>
<td>2 mo/DOD</td>
</tr>
<tr>
<td>4</td>
<td>ACC</td>
<td>Adrenal gland</td>
<td>F</td>
<td>58</td>
<td>C228T</td>
<td>No</td>
<td>7</td>
<td>None</td>
<td>105 mo/AWED</td>
</tr>
<tr>
<td>5</td>
<td>ea PGL</td>
<td>Urinary bladder</td>
<td>M</td>
<td>46</td>
<td>C228T</td>
<td>Yes a</td>
<td>–</td>
<td>Yes/LNs</td>
<td>NA</td>
</tr>
<tr>
<td>6</td>
<td>ea PGL</td>
<td>Urinary bladder</td>
<td>M</td>
<td>61</td>
<td>C228T</td>
<td>Yes b</td>
<td>–</td>
<td>Yes/LNs</td>
<td>226 mo/AWED</td>
</tr>
<tr>
<td>7</td>
<td>GIST</td>
<td>Stomach</td>
<td>F</td>
<td>57</td>
<td>C250T</td>
<td>Yes c</td>
<td>–</td>
<td>––</td>
<td>33 mo/DOD</td>
</tr>
</tbody>
</table>

ACC, adrenocortical carcinoma; AWED, alive without evidence of disease; DOD, dead of disease; ea PGL, extra-adrenal paraganglioma; GIST, gastrointestinal stromal tumor; LN, lymph nodes; NA, not available.

aSDHB IHC/SDHA IHC as previously published in Korpershoek et al. (2011) (non-informative on mutational analysis due to poor DNA quality).


cSDHB IHC/SDHA IHC+ (SDHD c.416T>C p.Leu139Pro).

Figure 1

Somatic TERT promoter mutations in ACC2 and G104 as detected using the Sanger sequencing method (upper panel) and confirmed using a SNaPshot assay (lower panel). Arrows in the upper panel indicate the C228T and C250T mutations as displayed in the sequencing chromatograms (from left to right), while arrows in the lower panel indicate the same mutations in the SNaPshot electropherograms.
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spectrum of cell lines. Approximately half that of the control HEK and SW13

TERT (ACAs), and adrenocortical carcinomas (ACCs) with or without cell lines, normal adrenocortical tissues (NATs), adrenocortical adenomas (ACAs), and adrenocortical carcinomas (ACCs) with or without TERT promoter mutations. TERT expression was measured relative to the housekeeping HPRT gene with fold changes normalized to expression in human adrenocortical tissue for all samples.

Figure 2

Quantitative real-time TERT expression analysis in human HEK and SW13 cell lines, normal adrenocortical tissues (NATs), adrenocortical adenomas (ACAs), and adrenocortical carcinomas (ACCs) with or without TERT promoter mutations. TERT expression was measured relative to the housekeeping HPRT gene with fold changes normalized to expression in human adrenocortical tissue for all samples.

level. Being consistent with the latter, LOH analysis revealed LOH both at the SDHAF2 and SDHD loci and for a microsatellite marker telomeric to SDHB gene.

Role of TERT promoter mutation in gene expression

To determine as to whether this mutation resulted in increased TERT expression, quantitative RT-PCR was performed on a single TERT promoter-mutated ACC for which frozen material was available. Significant TERT expression was detected in the promoter-mutated ACC, while the non-mutated ACCs demonstrated very low to negligible TERT expression similar to that detected in normal adrenocortical tissue as shown in Fig. 2. TERT expression in the TERT promoter-mutated ACC was approximately half that of the control HEK and SW13 cell lines.

Discussion


Interestingly, we found that two ea PGLs of urinary bladder harboring TERT promoter mutations were SDH-deficient tumors. Other tumors that have been linked to SDH deficiency are GISTs (Barletta & Hornick 2012). To further explore a potential association between the presence of these mutations and SDH deficiency, a series of 36 GISTs were examined and subsequently revealed one SDHD-mutated GIST containing a TERT promoter mutation. This prompted us to examine the SDH status of the TERT promoter-mutated ACCs. Despite the fact that this latter tumor type has never been associated with SDH deficiency, we showed loss of SDHB expression in one of the aforementioned ACCs, but without any germline SDH-x pathogenic mutations or gross deletions detected. This finding further extends the spectrum of tumors displaying loss of SDHB and/or SDHA expression in the absence of causative SDH-x mutations, including a clinicopathologically and biologically distinctive subset of KIT/PDGFRα WT GISTs (Barletta & Hornick 2012, Nannini et al. 2013), poorly and/or un-differentiated NBLs (Feichtinger et al. 2010), and a clear cell RCC with sarcomatous dedifferentiation (Papathomas et al. 2013).

Although only a small subset of SDH-deficient ea PGLs and GISTs harbored a TERT promoter mutation, the latter did occur exclusively in the SDH-deficient setting. As all SDH-deficient TERT promoter-mutated tumors were clinically aggressive, these observations may reflect that TERT promoter mutations can cooperate in SDH-deficient cells to support an enhanced tumor progression. Whether or not the latter could be attributed to telomerase-mediated extension of telomeres extending the lifespan of mutated clones, conferring them infinite proliferation potential as well as enabling the accumulation of additional genetic alterations, and/or to other non-canonical functions interfering with extra-telomeric tumor-promoting pathways remains to be elucidated (Greider & Blackburn 1985, Cao et al. 2002, Stewart et al. 2002, Choi et al. 2008, Parkinson et al. 2008, Park et al. 2009, Martinez & Blasco 2011, Mukherjee et al. 2011, Liu et al. 2013b).

Similarly, a selective combinatorial genetic alteration pattern has been highlighted in various tumor types (Arita et al. 2013, Horn et al. 2013, Killela et al. 2013, 2014, Landa et al. 2013, Liu et al. 2013a, Tallet et al. 2013,
In CNS tumors, TERT promoter mutations mostly occur in i) tumors with EGFR amplification, ii) IDH WT tumors, iii) almost all tumors with concurrent total chromosome 1p and 19q loss and IDH1/IDH2 mutations, and iv) IDH1/IDH2-mutated tumors exhibiting oligodendrogial morphologies (Arita et al. 2013, Killela et al. 2013, 2014). Similar to the previously reported coexistence with BRAF-activating mutations or with concomitant BRAF and CDKN2A alterations in melanomas (Horn et al. 2013, Heidenreich et al. 2014, Pópulo et al. 2014), two independent groups displayed a preferential occurrence of TERT promoter mutations in BRAF V600E mutation-positive papillary thyroid carcinomas (Liu et al. 2013a, Vinagre et al. 2013), while Landa et al. (2013) observed a significant co-occurrence of TERT mutations with BRAF and RAS mutations in poorly differentiated thyroid carcinomas and anaplastic thyroid carcinomas. In bladder cancer and mesotheliomas, TERT promoter mutations were frequently associated with inactivating mutations in the TP53/ RB1 signaling pathway (Wu et al. 2014b) and tumor suppressor CDKN2A gene inactivation respectively (Tallet et al. 2013), while a significant co-occurrence with CTNNB1-activating mutations has been reported in hepatocellular carcinomas and adenomas with malignant transformation (Nault et al. 2013, Pilati et al. 2014).

In this study, all TERT promoter-mutated tumors except one appeared to be metastatic (Table 1); this being in accordance with previous studies demonstrating that these mutations are more highly prevalent in advanced forms of particular malignancies, including follicular cell-derived thyroid cancer, melanoma, and primary glioblastoma (Horn et al. 2013, Killela et al. 2013, Landa et al. 2013, Liu et al. 2013a,c, Vinagre et al. 2013). By contrast, TERT promoter mutations occur as an early genetic event in bladder tumorigenesis (Kinde et al. 2013, Allory et al. 2014, Hurst et al. 2014), meningiomas prone to malignant progression (Goutagny et al. 2013), as well as in CTNNB1-mutated hepatocellular adenomas associated with the last step of the adenoma–carcinoma transition (Nault et al. 2013, Pilati et al. 2014). In this context, BRAF V600E-mutated papillary thyroid carcinomas, which are more aggressive than their BRAF WT counterparts (Liu et al. 2013a), are preferentially enriched for TERT promoter mutations (Liu et al. 2013a, Vinagre et al. 2013).

TERT promoter mutations seem to be present in NBLs at low frequencies (~9%; two out of 22; Killela et al. 2013). NBLs are characterized by high expression and/or amplification of NMYC, the neuronal equivalent of c-myc. A direct binding of NMYC to the TERT promoter has not been established. In this study, TERT promoter mutations were not detected in any peripheral neuroblastic tumor being consistent with the data stemming from a recent whole-genome sequencing project for NBLs (Molenaar et al. 2012) and similar observations concerning other pediatric embryonal tumors, such as a clinically distinct molecular subtype of medulloblastoma (Killela et al. 2013, Koelsche et al. 2013, Remke et al. 2013). Nevertheless, three human NBL cell lines harbored TERT promoter mutations indicating that lack in tumor samples could be attributed either to decreased sensitivity of the technique owing to the presence of normal cells or to the inclusion of other peripheral neuroblastic tumor types, such as ganglioneuroblastomas and/or ganglieneuromas.

In summary, this study demonstrates that TERT promoter mutations occur, albeit rarely, in tumors originating from the adrenal cortex (ACCs) and extra-adrenal PGLs. Their absence in PCCs and HN PGLs indicates that these seem unlikely to be critical genetic events in their development and/or progression. In addition, it provides preliminary evidence of a potential association with the acquisition of TERT promoter mutations in a subset of aggressive SDH-deficient tumors. Further studies are warranted to elucidate this connection and to provide mechanistic insights into the effects of these gain-of-function mutations at the TERT promoter on SDH-x-related tumorigenesis as well as their prognostic relevance in SDH-related tumor types.

**Supplementary data**
This is linked to the online version of the paper at http://dx.doi.org/10.1530/ERC-13-0429.

**Declaration of interest**
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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